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CONVERSION OF A C-11B INSTRUMENT FLIGHT TRAINER INTO A VARIABLE STABILITY FLIGHT SIMULATOR

by

Charles John Sweeney

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THESIS

CONVERSION OF A C-11B INSTRUMENT

FLIGHT TRAINER INTO A VARIABLE STABILITY

FLIGHT SIMULATOR

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Charles John Sweeney, Jr.

September 1968

[redacted]

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Charles John Sweeney, Jr.
Lieutenant Commander, United States Navy

[redacted]

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ABSTRACT

A C-11B Instrument Flight Trainer was converted into a variable stability flight simulator. The original frame, cockpit, controls, pneumatic system and instruments were utilized as well as certain other necessary components. The original aerodynamic and engine computers were removed, a new instrument drive system was designed and a hybrid computer was programed to solve the equations of motion. The cockpit controls supplied the inputs to the computer which in turn supplied the outputs to the various instruments through their respective drive systems. The computer program may be quickly changed to simulate the aerodynamic characteristics of almost any single engine jet aircraft, or the parameters of a specific aircraft may be varied to investigate their effects on flying qualities.

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A reasonably good simulator could have been designed and built; but inasmuch as a Link Aviation model C-11B "Jet-Propelled Aircraft Instrument Flying Trainer," as shown in Figure 1, was available, it was decided to modify the subject trainer. The design, modification and testing of the variable stability flight simulator were conducted at the Naval Postgraduate School, Monterey, California, during the period March 1968 through September 1968.

The author wishes to express his appreciation to: Mr. Walter Landaker for his design of the instrument drive system, Mr. Dana Maberry for his wiring of the simulator, Mr. Bertis Funk for his modification of the pneumatic system, Dr. George Rahe and Mr. Robert Limes for their assistance on the hybrid computer and, in particular, Professor Donald Layton for his invaluable assistance and advice while pursuing this project. The author is especially indebted to his wife, Diane, for her patience and understanding during the modification of the simulator and the preparation of the thesis.

CHAPTER I

INTRODUCTION

The Department of Aeronautics of the Naval Postgraduate School had a requirement for a variable stability flight simulator to be used as an instructional aid in the various courses in the aeronautics curriculum such as flight dynamics, flight performance and automatic flight controls. The simulator was also to be used as a research vehicle for various thesis projects such as flight instrumentation, automatic fligh controls, pilot response and flying qualities. The simulator had to be reasonably simple to operate and understand, had to faithfully simulate the response of the programed aircraft and had to be capable of being quickly and easily reprogramed.

A flight simulator should reproduce the flight characteristics of the aircraft which it represents. The pilot sees and feels the aircraf characteristics by means of his controls and flight instrument display as well as other visual cues if they are available. When one or more of the important parameters that determine the response of the simulate aircraft can be varied, the simulator becomes a variable stability sim

The requirement that the simulator should not only respond like th actual aircraft but should also have a cockpit that resembles an aircra cockpit eliminated the use of a rudimentary simulator which might cons of a control stick, computer and a few flight instruments. In additio motion feedback cues were also desired to augment the various visual cues in achieving realism. Many other features were also desired, but the main requirements for the simulator were flexibility, simplicity of operation and faithful reproduction of the aircraft characteristics

FIGURE 1. Overall View of C-11B Instrument Flight Trainer Prior to Modification

CHAPTER II

DESCRIPTION OF THE ORIGINAL TRAINER

The C-11B trainer (Navy designation 2F23 Training Device) was designed by Link Aviation, Inc., of Binghamton, New York, in 1951 to instruct jet pilots in the techniques of basic instrument flying as well as in the use of radio navigational aids.[1] This usage differs from that of an operational flight trainer which is designed to reproduce every feature of a specific aircraft in order to teach pilots basic flying techniques, emergency procedures and tactics in that aircraft. Inasmuch as the C-11B trainer was not designed as an operational flight trainer, it does not simulate the response of any specific aircraft but only approximates the dynamic response of a typical jet aircraft of the F-80 type.

The C-11B trainer, as shown in Figure 1, was 18 feet 5 inches long, 5 feet wide (without the staircase) and 9 feet 4 inches high. The steel frame was covered with removable paneling and was sectionalized into four main parts. The two rear sections contained the instructor's console, air conditioner, main power distribution panel and most of the electronic and electro-mechanical computers associated with the radio navigational aids. The two forward sections contained the cockpit, pneumatic control system and the various computers used for the flight and engine instruments.

The trainer employed an a. c. carrier computer of 60 Hertz to perform the various mathematical operations required to simulate an aircraft. Servo systems were used for integration, multiplication, trigonometric resolution and function generation while a. c. summing amplifiers were extensively used as buffers and summers. Unfortunately, the trainer utilized vacuum tubes rather than solid state devices which created heating and reliability problems as well as requiring greater space and higher power. The various chassis were mounted on sliding racks beneath the cockpit deck as well as beneath the instructor's console and required the use of four large ventilation fans for cooling.

The cockpit, as shown in Figure 2 and which was configured similar to that of the F-80 jet aircraft, was covered with a hooded movable canopy. The canopy lighting could be varied to simulate complete darkness, daylight in an overcast and lightning flashes. The instrument dials were fluorescent and were activated by two infra-red lights. A sound system was also incorporated to simulate turbine whine, jet exhaust blast and slipstream sound. In addition, an interphone system between the pilot and the instructor was used to simulate radio and navigational facilities as well as static. The trainer was of the fixed base type, and all simulation was achieved by visual rather than motion cues.

The control stick and rudder pedals had a variable load placed on them to represent the loading of the simulated control surfaces. This load varied with dynamic pressure and was achieved by a pneumatic system consisting of an air compressor, tanks, valves, pistons and necessary plumbing. This system was located forward of the cockpit as shown in Figure 3. The elevator and aileron controls also used trim motors to simulate trim tabs by movement of the loading cylinders and the control stick.

The trainer used d. c. milliameters with appropriate calibrated dial faces for most of the engine instruments including two non-functional instruments (the load meter and the oil pressure indicator). The various computers used in the trainer calculated and varied the readings of the

FIGURE 2. Cockpit and Instrument Panel of C-11B Prior to Modification

Figure 3. Close View of Loading Cylinders and Pneumatic System Prior to Modification

following engine instruments: fuel quantity, rate of fuel flow, fuel pressure, hydraulic pressure, jet exhaust temperature and outside air temperature.

The primary flight instruments were driven by individual computers using two slightly different methods. The first method used the computer to position a synchro transmitter which was located on the computer chassis. This in turn positioned a synchro receiver located within the simulated instrument, turning the required needle or dial. The following instruments employed this method: altimeter, indicated air speed, maximum allowable indicated air speed, Mach number, heading, vertical speed, rate of turn and ball (commonly referred to as needle-ball) and the navigation instruments.

The second method used a servo motor and induction generator within the instrument itself to drive the appropriate indicator. This method eliminated some of the gearing required and reduced the required number of servo chassis. The accelerometer (g-meter), tachometer and attitude gyro (gyro horizon) utilized this method.

The instructor's console had duplicate airspeed, heading and altimeter indicators as well as various controls to simulate different weather conditions. Rough air of varying intensity could be programed as well as such variations as lightning, icing, changing light intensity, varying cloud intensity and winds. In addition a ground position recorder and an instrument landing system recorder were also installed at the instructor's console.

CHAPTER III

BASIC MODIFICATION OF THE TRAINER

The first problem encountered in the modification was the decision as to what components should be retained for use in the simulator and what components could be used for other projects. The first step in making this decision was the establishment of criteria for the characteristics of the variable stability simulator. This was followed by a detailed analysis of the systems employed by the C-11B trainer. Finally, the various solutions of the simulation problem were evaluated with the usual monetary and time restraints playing a predominant role.

Personal liaison was established with the simulation laboratories at the Naval Air Missile Test Center, Point Mugu, California, and NASA Ames Research Center, Moffett Field, California, in order to view the various basic and advanced flight research simulation facilities that were available and to discuss current and proposed simulation techniques. In addition, discussions were held on present and future simulation techniques with personnel from the Link Group, General Precision, Inc., Binghamton, New York.

One of the principal requirements in the development of a variable stability simulator is the ability to change the dynamics of the simulated aircraft easily and quickly. This is necessary so that various aircraft can be represented by the same simulator or so that one or more of the characteristics of the same aircraft can be varied. The computers used in the original trainer did not have this capability, so it was necessary to provide an external computer system to solve the differential equations of motion of the simulated aircraft.

The analog computer has traditionally been the principal tool for aeronautical research simulations since it can directly solve equations of motion in real time and can be easily programed. However, it has some precision limitations. On the other hand, a digital computer is extremely precise but has real time limitations and requires converters for the various input-output connections to the simulator. A hybrid computer combines the best characteristics of both types, so the decision was made to utilize the hybrid computer facility that was available at the Naval Postgraduate School to solve the equations of motion.

The feasibility of adding motion cues to the original trainer was also investigated. This would have required hydraulic jacks to move the entire trainer as well as additional computer capability to provide for the control of the associated valves. It was felt that the improvement offered by the motion cues would not offset the large additional expense of a motion system.

A classroom was converted into a simulator laboratory to house the modified simulator and its associated equipment. This room was located 90 feet from the hybrid computer and had a cable trench in the deck which connected the laboratory with the computer room. The simulator required a source of three wire, 230 volt, 60 Hertz, single phase power which was obtained by the installation of a circuit breaker panel and the necessary conduit, receptacles and cables. In addition, the air conditioner and its associated controls were removed from the trainer and installed in the laboratory with the required ducting to cool the entire room.

Some of the features of the original trainer were not utilized in the modified simulator for several reasons. Some systems were not applicable to the simulator, others were not economically feasible to use at the time and the engineering time involved in utilizing still others was considered to be too great for the minor advantages achieved. As a result, some of the systems were completely removed while others were retained, but are inactive.

The following systems were removed from the original trainer: all radio and navigation aids (except for the controls) including tacan, omni, ADF, ILS, GCA, range and marker beacon; ground position recorder; instrument landing system recorder; interphone; sound system including engine turbine whine, jet exhaust blast and slipstream sound; pitot ice; lightning effects; gyro precession and wind vectors. Most of the components of the following systems were retained but are not activated: stall warning stick shaker, landing gear, flaps, speed brakes, foot brakes, parking brake, landing gear warning horn, emergency fuel pump, magnetic variation, barometric pressure, pitot heat, rough air, maximum indicated airspeed, Mach number and ID249 course selector.

CHAPTER IV

CONTROL LOADING SYSTEM

A proposed future simulator project is the presentation of external visual cues in addition to those obtained from the cockpit instruments. This could be achieved by such means as the use of an optical projector to place the display on a screen located outside the cockpit, the direct viewing of a video picture tube or a contact analog device. The use of any of these devices introduced a requirement to shorten the simulator forward of the cockpit in order to increase the external visual field of the pilot.

The forward 3 feet 2 inches of the original trainer were removed by cutting off the two front sections. The amount to be removed was dictated by the extent of the forward travel of the movable canopy. The necessary access panels were then cut to size, the two nosecap sections were re-installed and the two rear sections were removed. The modified simulator, as shown in Figure 4, has an overall length of 7 feet 10 inches (10 feet 7 inches shorter than the original trainer), a height of 7 feet (2 feet 4 inches shorter) and a width of 7 feet 6 inches which was the width of the original trainer with the staircase to the cockpit installed.

In the original trainer, the elevator, aileron and rudder control loading cylinders as well as the compressor, air supply tanks, filters, valves, pistons and associated plumbing of the pneumatic system were located well forward of the cockpit. The shortened frame required the relocation of the entire pneumatic system while retaining all of the characteristics of the system.

The rudder control loading cylinder was remounted on the underside of the deck of the cockpit on the right side in an inverted position as

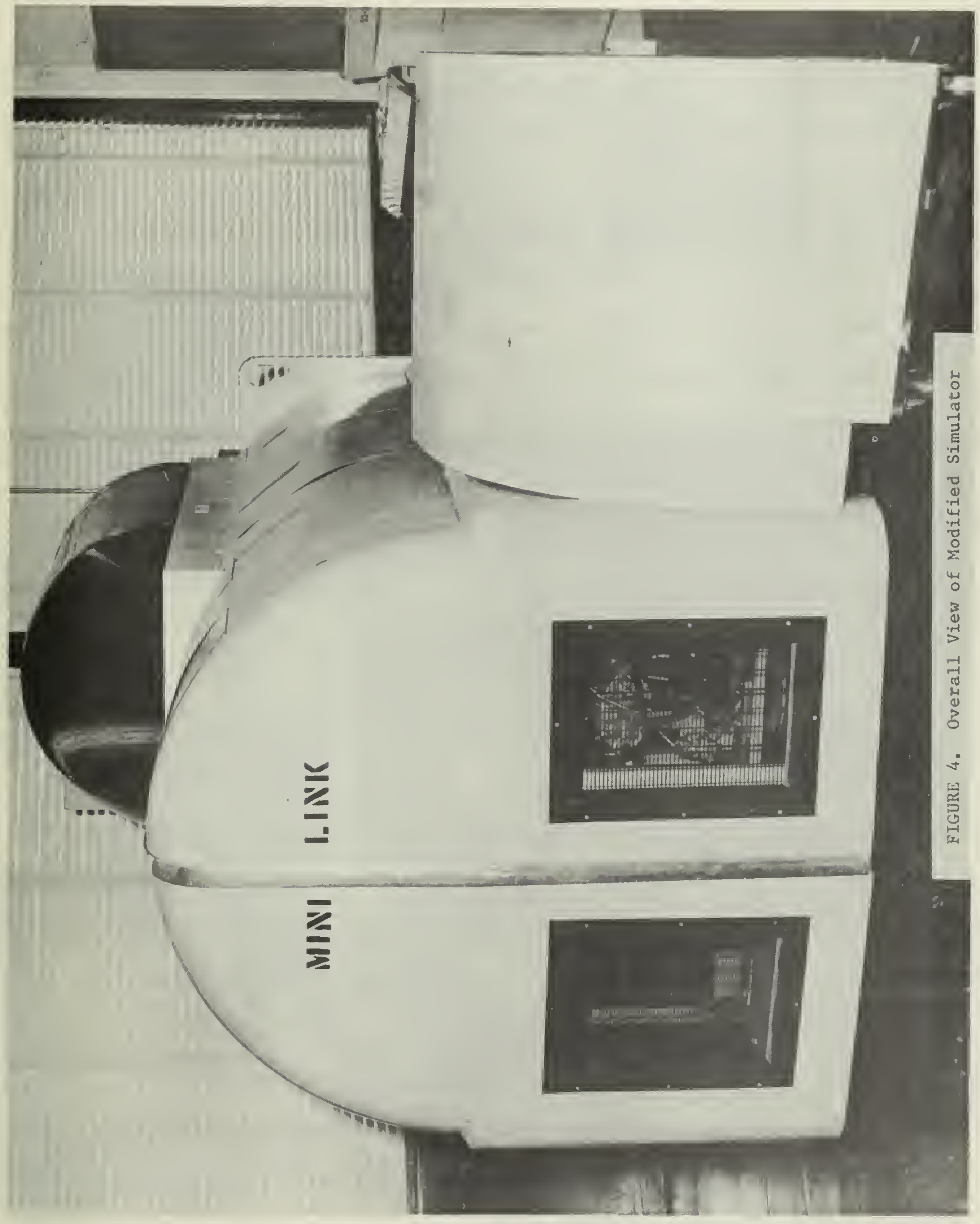

FIGURE 4. Overall View of Modified Simulator

shown in Figure 5. The linkage system to the rudder pedals remained basically the same, therefore, no changes were required in that portion of the loading system. There was no trim associated with the rudder, consequently, the only output wiring required was from the potentiometer that was directly geared to the cylinder movement.

The aileron and elevator control loading cylinders utilized hydraulic dash pots which precluded mounting these cylinders in an inverted position. Therefore, both cylinders were mounted on the base of the simulator frame below the cockpit with the aileron control cylinder located on the outboard side as shown in Figure 5. The linkage from the control stick to the cylinders had to be modified slightly, but the resultant change in the mechanical advantage was not considered to be detrimental inasmuch as the loading pressure could be changed to compensate for the modification.

Both the aileron and elevator controls used trim motors to simulate the trim tabs in an actual aircraft. The actuating switch was located on the top of the control stick and had 4 positions; up or down elevator and left or right aileron. This switch controlled motors that moved both the cylinders and the control stick. The motors also drove cam-operated limit switches and cam-operated neutral switches. The latter switches activated indicator lights in the cockpit.

After the trainer was shortened, the motor, compressor, tanks, valves, filters and slightly modified plumbing for the pneumatic system were retained in the original frame which was then mounted on casters, covered with removable access panels and stationed by the left side of the simulator as shown in Figures 4 and 5. The various interconnecting flexible air hoses and electrical cables could be quickly disconnected for maintenance of the cylinders or for access to other units in the forward portion of the simulator.

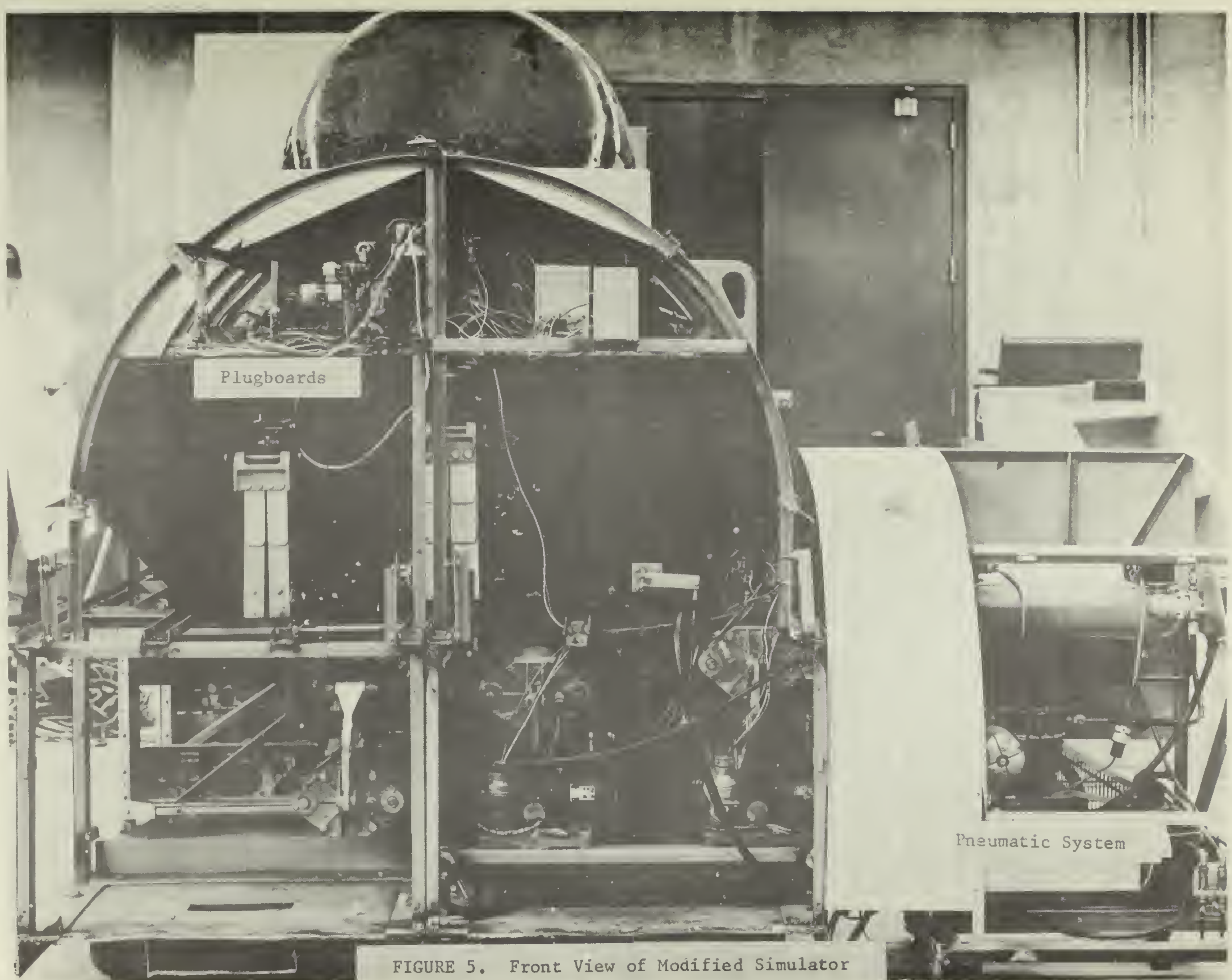

FIGURE 5. Front View of Modified Simulator

The original trainer utilized a switch activated valve to simulate the employment of an aileron boost system. This feature was retained in the simulator so that activation of the valve resulted in lower pressure on the aileron control cylinder. In addition, the pneumatic system contained a "stall spill" valve which could be activated to cause all the controls to mush out, as would be the case in an aerodynamic stall.

The original trainer used the computed value of dynamic pressure to vary the simulated loading on the controls. This capability was retained for future projects, but for the initial phase, a predetermined value of control loading is set by use of a switch.

CHAPTER V

POWER DISTRIBUTION AND WIRING

Inasmuch as the modified simulator utilized many of the original components as well as some new components, the power requirements were quite extensive and varied. Some of the various 60 Hertz, single phase a. c. voltages required were: 230 volts for motors, 115 volts for transformers and lighting, 32 volts for synchros, 18.5 volts for instruments and 6.3 volts for lights. The necessary d. c. voltages were: +48 volts for instruments and relays, +24 volts for instruments and +15 volts for transistors. In addition, 26 volts, 420 Hertz, single phase was needed for one of the instruments.

The main power distribution panel was removed from the instructor's section and was remounted on the back of the cockpit as shown in Figure 6. This panel contained the necessary switches, relays, timers, transformers, fuses and elapsed time meter required for the power control and distribution. The 230 volts, 115 volts, 32 volts and 6.3 volts, 60 Hertz power was supplied by this panel. A flexible power cable was used to connect the simulator power distribution panel with the fixed main power circuit breaker panel in the laboratory. This permits movement of the simulator to any location in the room.

A source of unfiltered +48 volts d. c. was required for various relays, instruments and lighting. A transformer and selenium rectifier were removed from a power supply chassis and remounted in an auxiliary power box which was installed next to the main power distribution panel as shown in Figure 6. This box also contained the controls for the pilot's hood lights and for the rough air system. The rough air system was not activated but is available for future use.

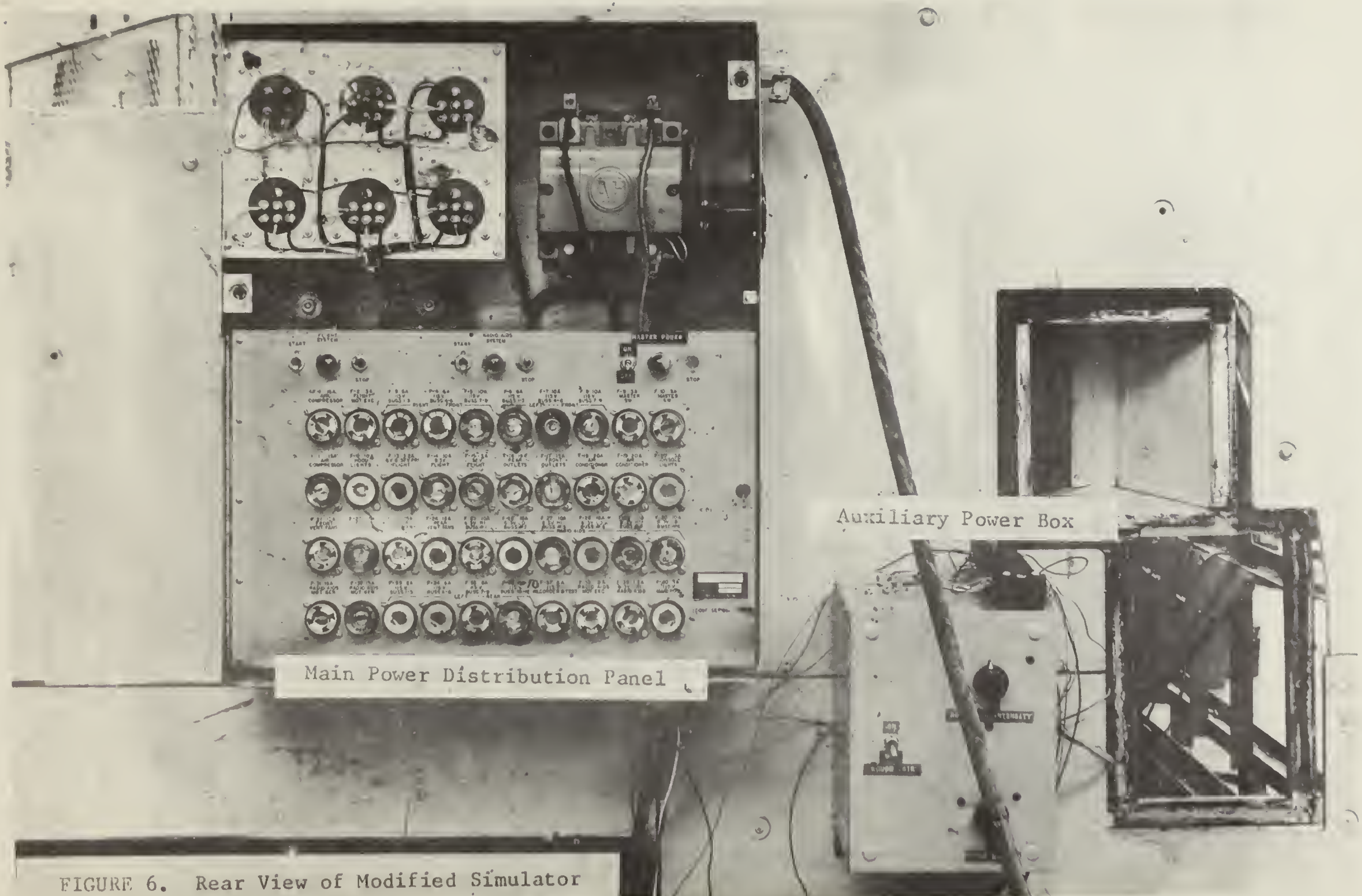

FIGURE 6. Rear View of Modified Simulator

The gyro horizon required 18.5 volts, 60 Hertz excitation for the motor-generator in the pitch system. This was obtained by removing a transformer from the instructor's section and remounting it below the cockpit at the rear of the right section. In addition to the transformer, a 10 microfarad capacitor was necessary to obtain the 18.5 volts, and this was mounted in the auxiliary power box with the voltage available at the terminal strip. The transformer also has a source of 90 volts available for future requirements.

The angle of attack indicator required a source of unfiltered +24 volts d. c. Since the +48 volt d. c. power supply was operating at its rated capacity, a different source had to be used. Another transformer and a selenium rectifier were removed from a chassis located in the instructor's section and were remounted on the left forward section of the simulator, behind the instrument panel.

Another instrument, the heading indicator or RMI, required a source of 26 volts, 420 Hertz for its operation. Since this power was not available in the laboratory, a motor-generator set was removed from the rear section of the trainer. This set consisted of a 26 volt, 420 Hertz generator driven by a 230 volt, 60 Hertz synchronous motor and was remounted below the cockpit on the left side of the simulator as shown in Figure 7.

The operational amplifiers and transistors used in the instrument drive systems required a source of +15 volts d. c. as well as a source of -15 volts d. c. These power sources had to be well regulated as well as having the ability to supply 1.5 amperes each when all the instruments were operating. Two model LA100-03BN d. c. power supplies made by Lambda Electronics Corp. were used since they could supply a well regulated 15 volts at 10 amperes.

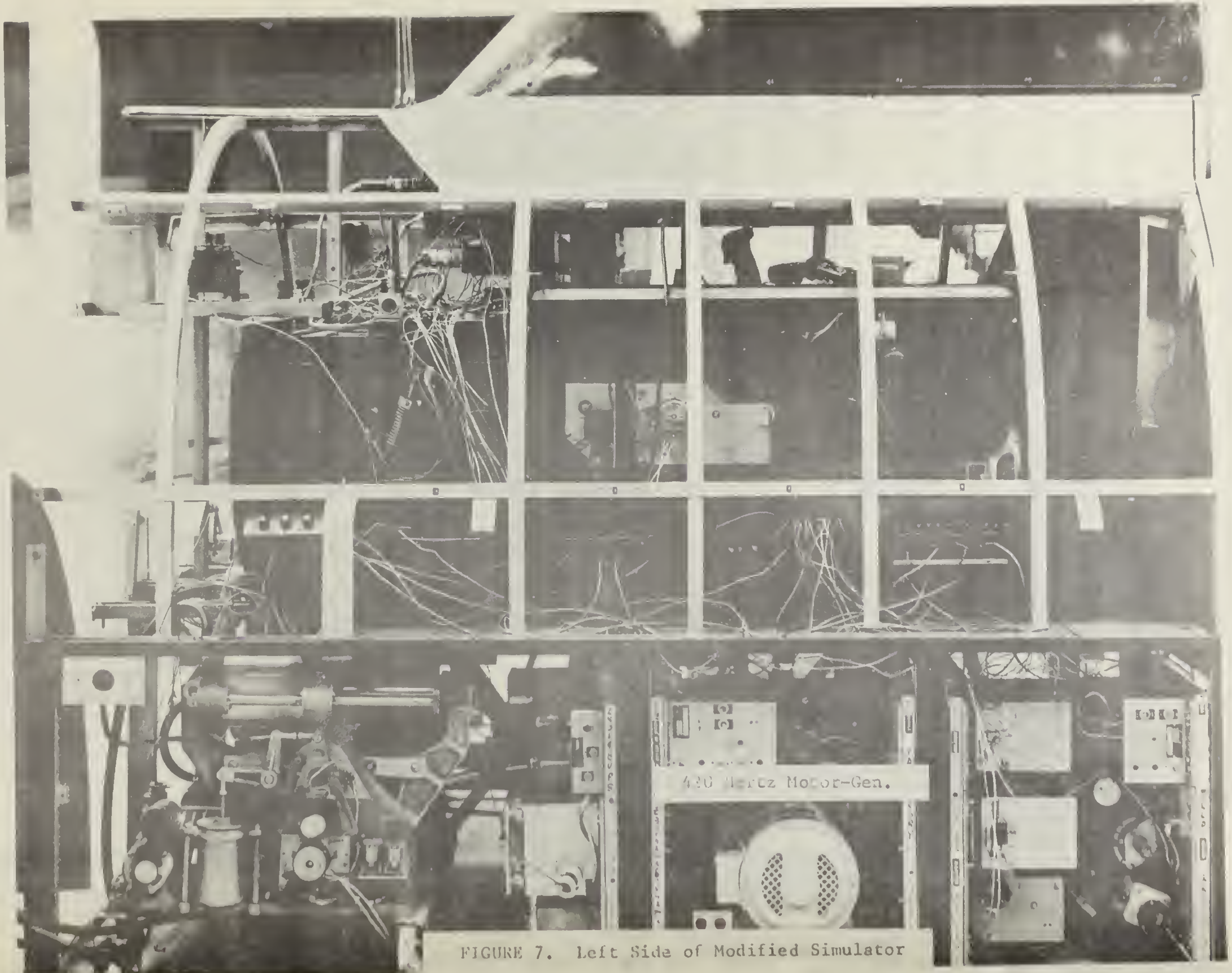

FIGURE 7. Left Side of Modified Simulator

Terminal strips were mounted on both sides of the cockpit to facilitate the various initial and proposed connections. This provided a greater flexibility to the system than would be available if the wires were run from chassis to chassis. It is proposed that in the future a patch board be mounted on the exterior of the simulator to further increase the flexibility.

Although it was planned to use the original wiring in the trainer, this did not prove to be possible, and all the original wiring was removed. The chassis required for the instruments were placed on the same side of the simulator as the instruments to minimize the wiring required. Inasmuch as the simulator is to be used primarily as a research vehicle which will require frequent modifications, no effort was made to bundle the new wiring into cables.

The original trainer used copper bus bars and the frame itself as the ground for the electrical system. In the modified simulator, the frame and bus bars were still utilized as the ground for the a. c. electrical system. However, all the d. c. input and output signals from the computer as well as the 15 volt d. c. power supplies used a common connection for the d. c. ground. This d. c. common was isolated from the a. c. ground and was run to the ground connection of the computer to minimize the possibility of noise being introduced into the system by ground loops.

Since the simulator was located approximately 90 feet from the computer in a different room, a 35 conductor cable, 100 feet long, was constructed from 16 gauge shielded wire. This cable also permits movement of the simulator to any location in the laboratory. One end used a Concoa type CR1-104P-SKH-SP connector to plug into the computer, and the shields were not connected together or to the computer on this end. Spade lugs were used on the laboratory end for connection with the terminal strips on the simulator, and all the shields were connected to the d. c. common. Only 17 of the conductors were used for the simulator while the remainder are spares for future use.

The original geared potentiometers on the elevator, aileron and rudder loading cylinders and on the throttle were of such low resistances that they could produce a loading effect on the computer, thereby greatly reducing the accuracy. Therefore, all the potentiometers were replaced by 100K, precision, wire wound, linear potentiometers, which were fused for protection. The potentiometers installed on the elevator, aileron and rudder loading cylinders required a tap at the center position that would indicate the neutral position, while the potentiometer on the throttle did not require a center tap. The potentiometer on the elevator loading cylinder required a method for mounting due to the difference in physical size between the old and new potentiometer, while the other potentiometers utilized the original mounting brackets. The original throttle potentiometer used a tapered resistance to represent the thrust as a non-linear function of throttle position. The replacement potentiometer was linear, but it was felt that the increase in accuracy more than offset the advantage of the nonlinearity, especially since the nonlinearity could be obtained through the computer circuits.

CHAPTER VI

FLIGHT AND ENGINE INSTRUMENTS

The most difficult problem encountered in the conversion was the design of the instrument driving systems. This was the very keystone of the entire simulation problem, inasmuch as the simulator would have no practical value without the proper visual cues for the pilot. These instruments have to faithfully simulate the response of actual aircraft instruments or else the pilot will sense the inadequacy of the simulation and will use a control technique that is different from the technique that he would employ in flying an aircraft.

The following instruments were considered to be of secondary importance for the simulation and were made nonfunctional: fuel quantity, fuel flow, fuel pressure, oil pressure, hydraulic pressure, load meter, jet exhaust temperature, outside air temperature and the gear and flap indicators. Since most of these nonfunctional instruments were d. c. milliameters, they were activated by the 48 volt d. c. power supply as shown in Figure 8. The potentiometers allowed the instruments to be set at a specified value which was at a standard operating altitude of 23,000 feet, and these potentiometers were mounted on a panel behind the right instrument panel. The gear and flap indicators were set to indicate the gear "up and locked" and the flaps "up" whenever the d. c. power supply was activated. In addition, the power off warning flag on the gyro horizon was retracted whenever the power supply was operating.

The simplest type of simulated flight instrument to use in fixed base simulators is a conventional d. c. meter movement with an appropriate dial face.[2] This is most suitable for single revolution instruments such as airspeed, vertical speed, accelerometer, angle of attack and

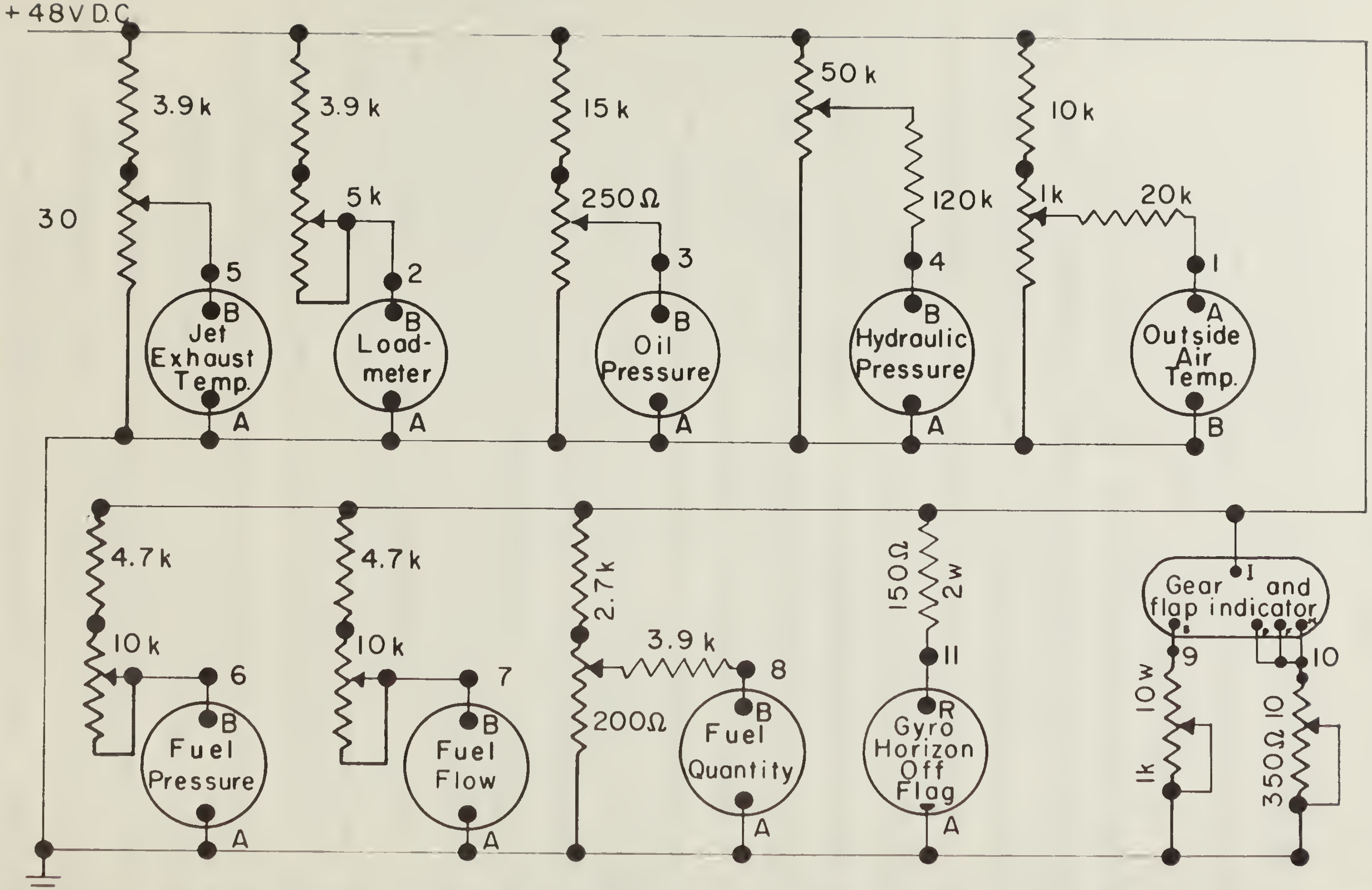

FIGURE 8. MODIFIED ENGINE INSTRUMENTS CIRCUIT.

possibly the tachometer. This type of instrument could have been operated directly from the computer but was prohibited due to monetary limitations. Another type of instrument frequently used in moving base simulators is the self-contained motor-driven pointer, but these were unavailable. The possibility of using a cathode ray tube for the various displays was discarded because of its lack of realism and its complexity.

The only practical solution to the instrumentation problem was to use the instruments installed in the original trainer. These instruments were: indicated air speed, altimeter, heading (RMI), vertical speed, needle-ball, gyro horizon, accelerometer and tachometer. An angle of attack indicator with its associated speed indexer was obtained for use in the simulator. The instrument arrangement was changed, and a new instrument panel for the left side was built and installed as shown in Figure 9. The new panel also allowed for the future installation of a 5 inch cathode ray tube.

The original trainer used an a. c. carrier computer to solve its simplified equations of motion and to drive its various instruments. This a. c. system offers several advantages over a comparable d. c. computer: The operational amplifier can produce both polarities of signals, the induction resolver is more accurate and requires less equipment and the system requires somewhat less power.[3] However, most laboratory analog computers are of the d. c. type, and the analog section of the hybrid computer being used falls into this category.

Since the instruments in the original trainer were driven either by an a. c. synchro system or by an a. c. motor-generator, a system had to be devised to drive the instruments with the d. c. signal output from the computer. Design of this system created the greatest problem in the entire conversion and was by far the most difficult to solve.

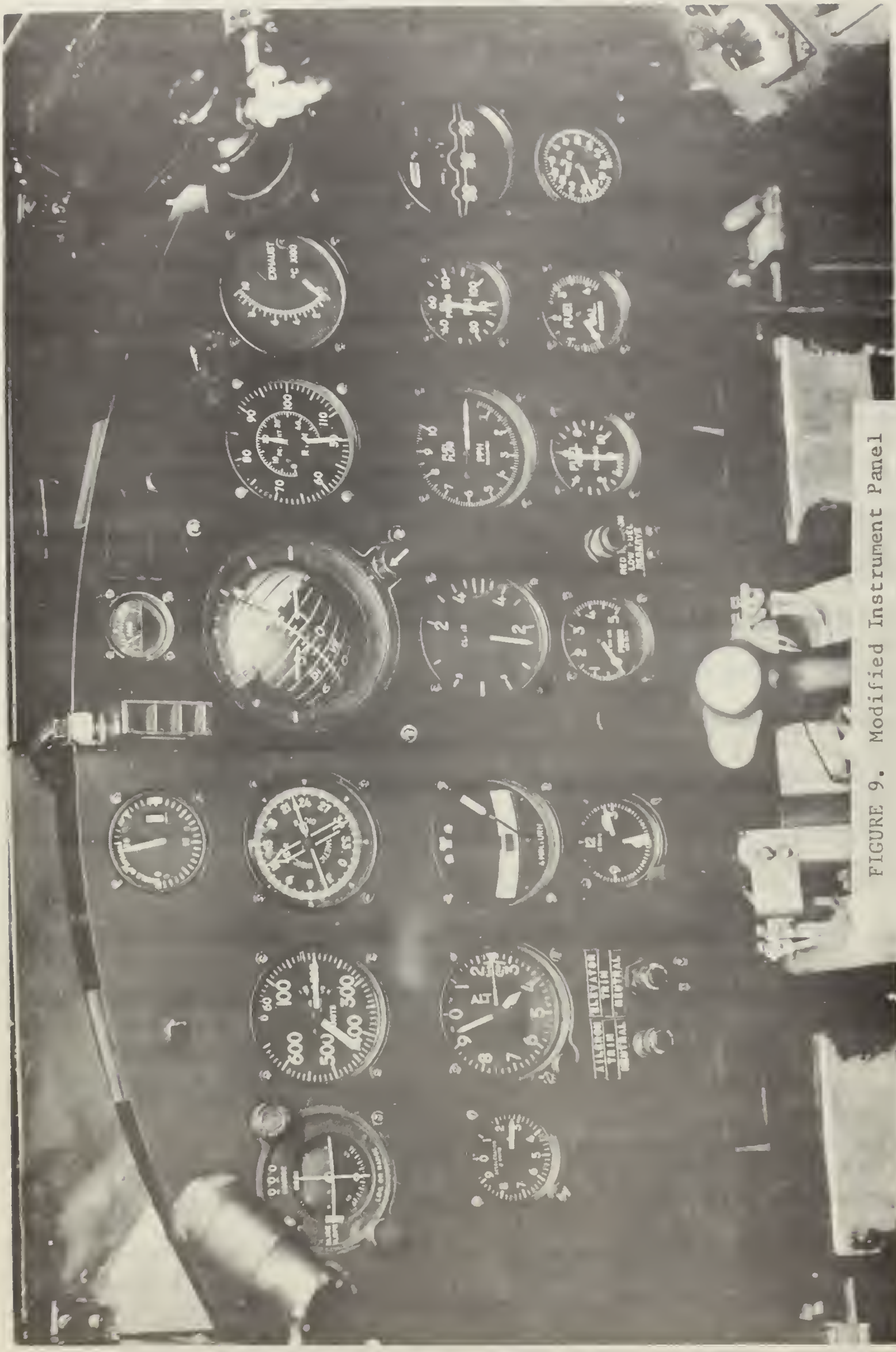

FIGURE 9. Modified Instrument Panel

Once it was determined that d. c. instruments could not be obtained, consideration was given to the utilization of the original instrument drive system by the conversion of the d. c. computer signal into an a. c. signal. This signal change could be accomplished by modulator elements such as a. c. choppers or vibrators, electronic modulators, ring modulators, transistor modulators or magnetic modulators.[4] However, this method was discarded since it would have required the use of the original a. c. servo amplifiers which employed vacuum tubes thereby creating extensive reliability, maintenance, alignment and cooling problems.

The airspeed indicator system was the first instrument drive system to be designed. The original indicated airspeed computer system, as shown in Figure 10, used the airspeed servo and the altitude servo to position two potentiometers. These potentiometers determined the value of the a. c. voltage that was proportional to the indicated airspeed. This a. c. signal was summed with an a. c. signal from the follow-up potentiometer to form an error signal.

The a. c. error signal was applied to the input of the a. c. servo amplifier and after amplification was used to drive a motor-generator. The motor-generator was geared to the follow-up potentiometer. The motor-generator drove until the error signal was zero which occurred when the follow-up signal was equal in amplitude but opposite in phase to the airspeed signal. The motor-generator also drove the rotor of a synchro transmitter through the appropriate gears. The rotor of the synchro receiver located in the airspeed indicator followed the movement of the transmitter rotor and was connected to the indicator needle.

The a. c. servo amplifier was mounted on one chassis, and the motor-generator, synchro transmitter, potentiometers and associated gears were

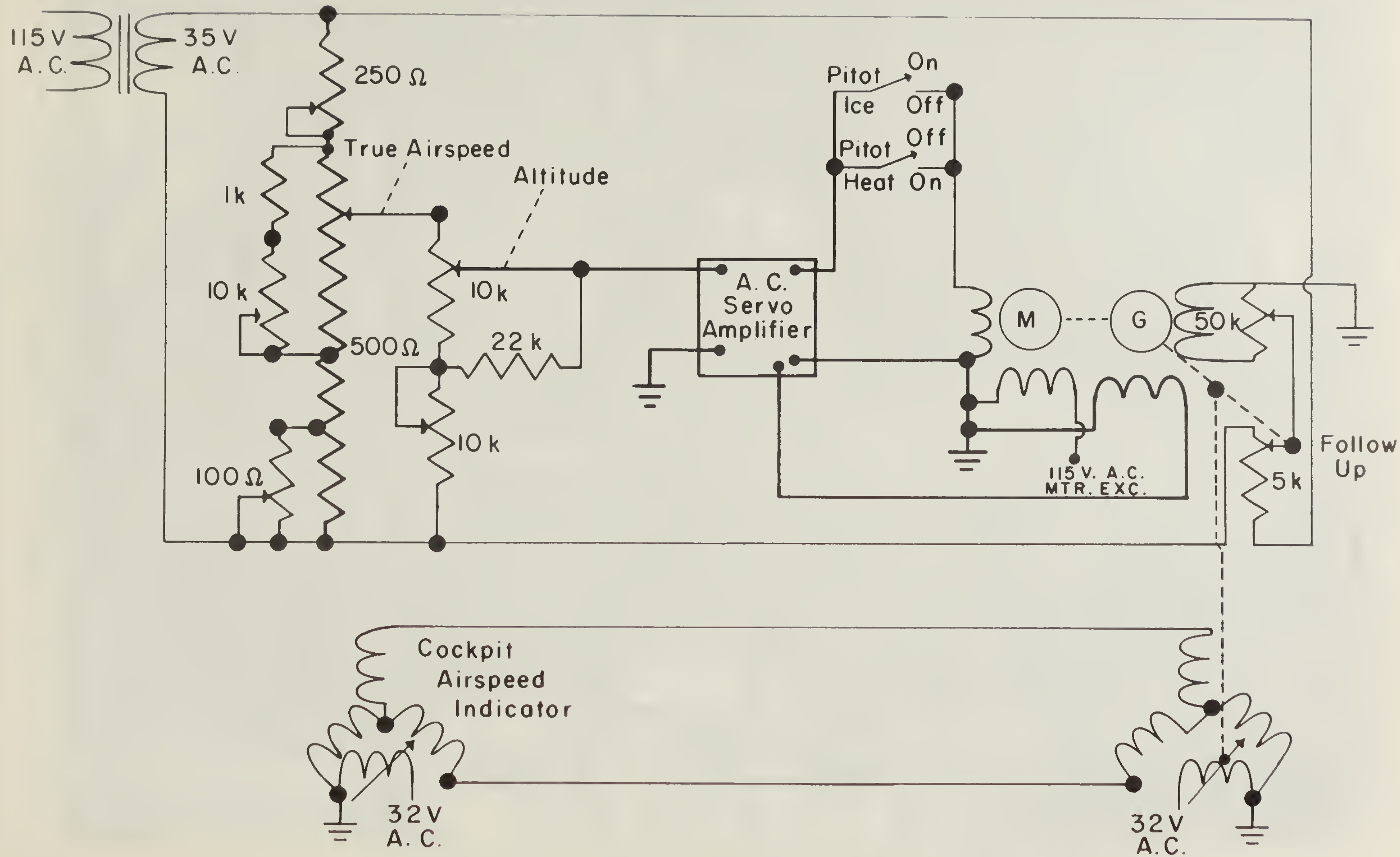

FIGURE 10. ORIGINAL INDICATED AIRSPEED COMPUTER CIRCUIT.

mounted on another chassis. The servo amplifier had a self contained d. c. power supply and only required 115 volts, 60 Hertz for its operation.

Since the airspeed signal output from the hybrid computer was a slowly varying d. c., it was decided to replace the a. c. motor generator with a d. c. motor mounted on the servo chassis to drive the synchro transmitter as well as the follow-up potentiometer through the original gear train. This replacement necessitated the use of a d. c. servo amplifier as well as a switching system to reverse the direction of the d. c. motor.

A supply of μA709C high-gain operational amplifiers was readily available; therefore, it was decided to use these as the d. c. servo amplifiers. The μA709C integrated circuit is a high-gain operational amplifier manufactured by the Fairchild Semiconductor Division of Fairchild Camera and Instrument Corporation on a single silicon chip.[5] It exhibits good temperature stability, low power consumption and tolerates a wide range of supply voltages. The integrated circuit, as shown in Figure 11, contains 14 transistors and 15 resistors in a 0.37 inch diameter package. Figure 12 dramatically shows the comparison in size of the d. c. servo amplifier with the a. c. servo amplifier which it replaced. The integrated circuit not only drastically reduces the space requirements but also greatly reduces the power requirements.

Once it was decided to use the integrated circuit as the d. c. servo amplifier, the next step was the design of the switching or control circuit. The most logical component for this circuit was the power transistor which requires very little input current to control a large amount of the output current. The design of the drive circuit

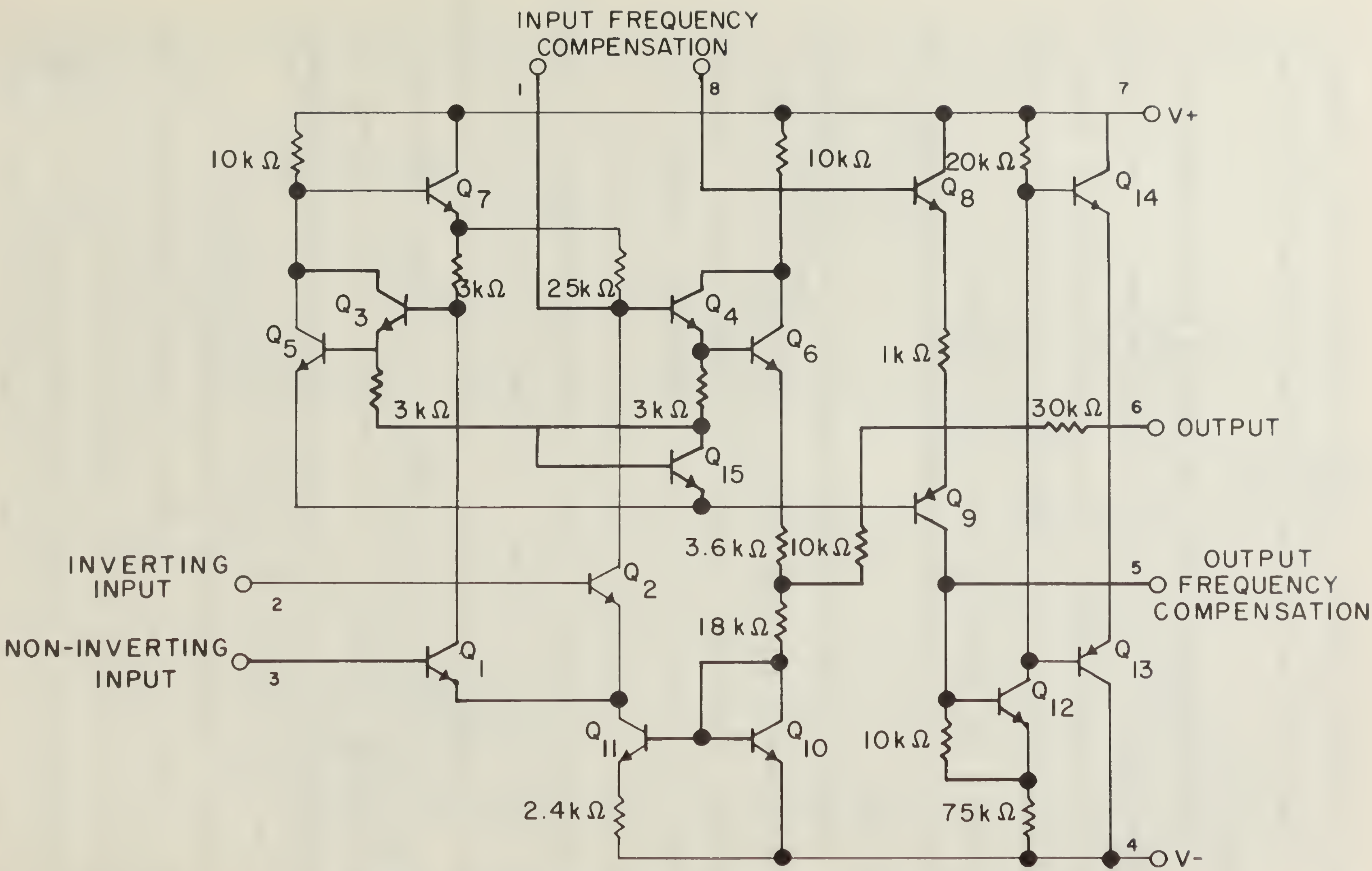

FIGURE II. μ A709C OPERATIONAL AMPLIFIER CIRCUIT.

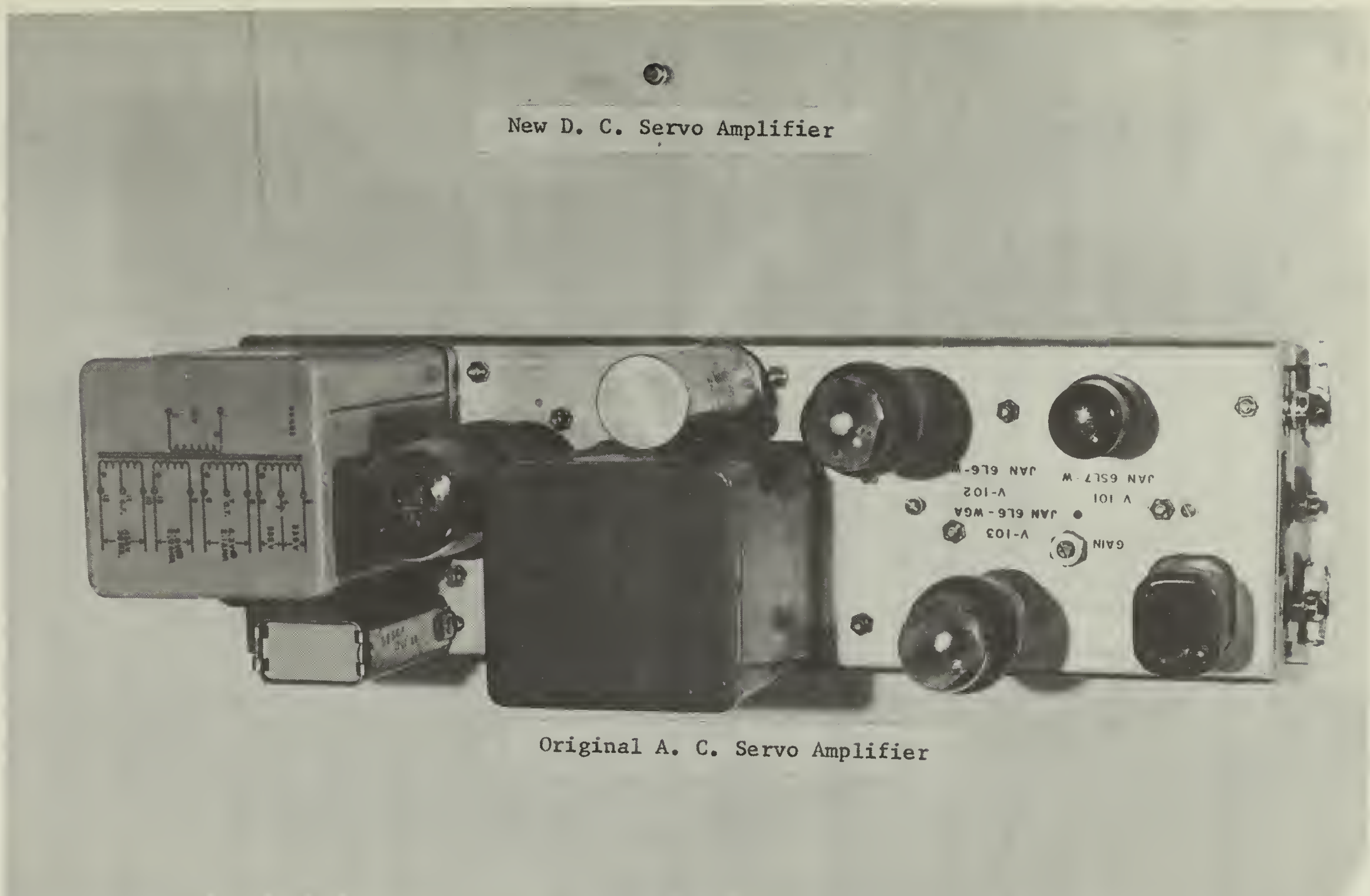

FIGURE 12. Comparison of A. C. Servo Amplifier with D. C. Servo Amplifier

required considerable experimentation. It was observed during this phase that, although the integrated circuit is quite rugged, it was ruined if the maximum supply voltage of 18 volts was exceeded or if the output was accidentally short circuited.

The final design of the instrument drive system, as shown in Figure 13, used the integrated circuit, two power transistors and associated resistors and capacitors. The d. c. signal from the computer, which is proportional to airspeed, is applied through a voltage divider network to the input of the operational amplifier. This voltage divider is necessary since the output of the computer can be as high as 100 volts while the maximum input to the operational amplifier may not exceed 10 volts.

The input signal is summed with a feedback signal and a follow-up signal to form an error signal which, after amplification, is applied to the base of a type 40250 N-P-N power transistor and the base of a type 2N235A P-N-P power transistor. Depending on the polarity and amplitude of the signal applied, one or the other of the power transistors will conduct, thereby applying either a positive or negative voltage to the d. c. motor. The polarity of the voltage determines the direction of rotation of the motor. The d. c. motor also drives a follow-up potentiometer which supplies a nulling voltage to the input of the operational amplifier and drives the rotor of the synchro transmitter. The rotor of the synchro receiver in the indicator follows this rotation and turns the needle on the dial.

During the testing of the drive circuit, it was noted that the instrument would follow the input better in one direction than in the other. It was felt that this was a minor discrepancy and could be corrected by the use of a matched pair of N-P-N and P-N-P transistors.

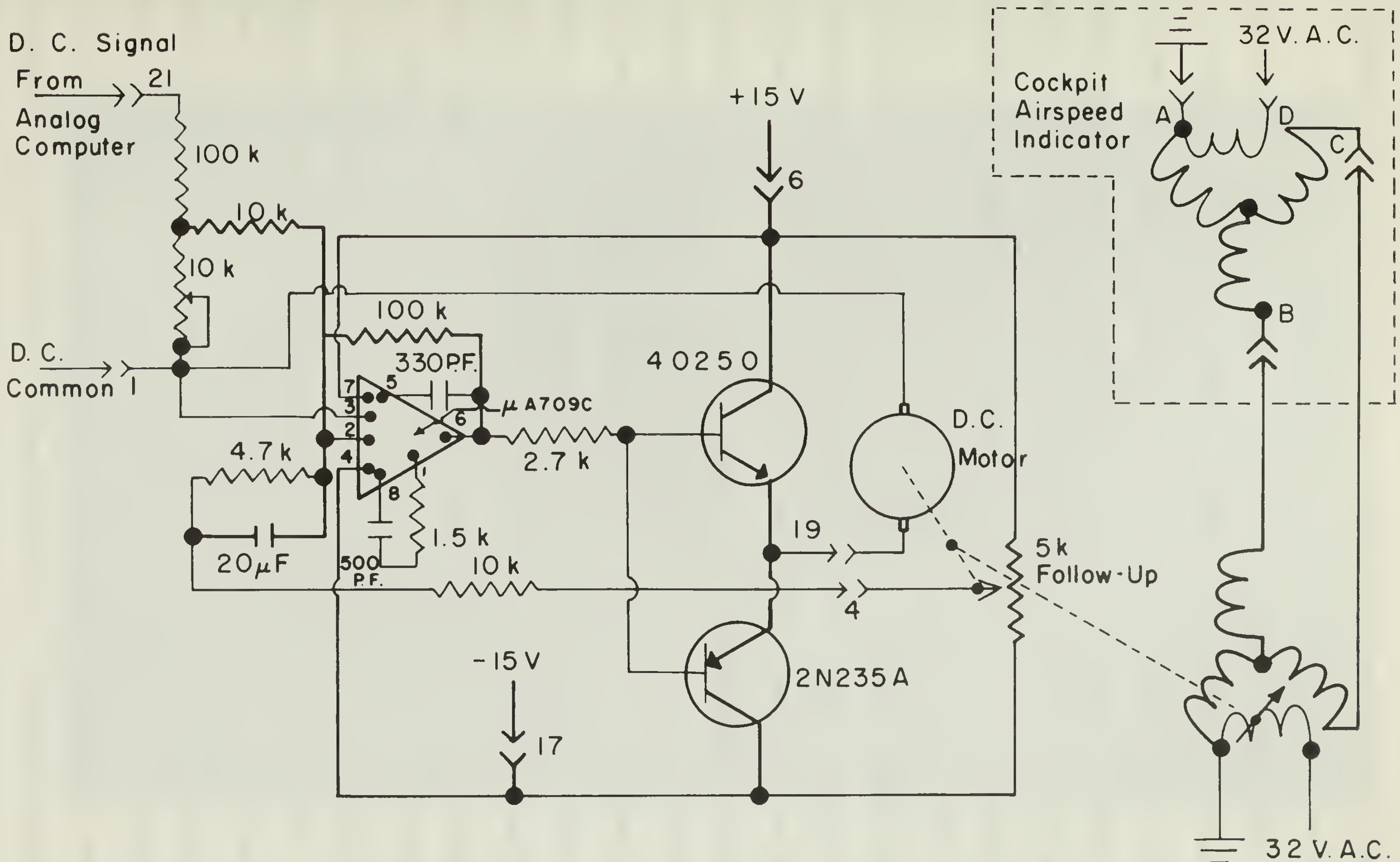

FIGURE 13. MODIFIED AIRSPEED INDICATOR DRIVE CIRCUIT.

However, these were not available at the time, and so the discrepancy remains.

The various components of the drive circuit were mounted on an etched contact plugboard as shown in Figure 14. This arrangement provided a very compact package, allowed for future expansion of the circuit and left the components accessible for testing and replacement as necessary. A total of 10 identical drive circuits were constructed on the plugboards and were used to drive the various instruments by one of three methods.

The first method consisted of removing the old wiring from the servo chassis and installing the plugboard, its mating receptacle, the d. c. motor and new wiring. The original follow-up potentiometer was used in most cases, and the d. c. motor drove the synchro transmitter on the servo chassis through the original gear train which in turn electrically drove the synchro receiver located within the instrument case. This made a compact package and used less space than the original system, as can be seen in Figure 15. The airspeed, heading, altimeter, needle-ball and vertical speed indicators use this method. Since the original system for the rate of turn needle did not use a servo chassis, another chassis had to be obtained and modified. In addition, the heading and altimeter drive systems required different follow-up potentiometers.

The angle of attack indicator uses a drive system that was similar to the previous method. The plugboard, mating receptacle, d. c. motor and wiring were installed on the servo chassis, and the original follow-up potentiometer was used. However, the d. c. motor drove another potentiometer in addition to the follow-up potentiometer instead of driving a synchro transmitter. The potentiometer is connected to the indicator as well as the 24 volt d. c. power supply, and the needle on the instrument

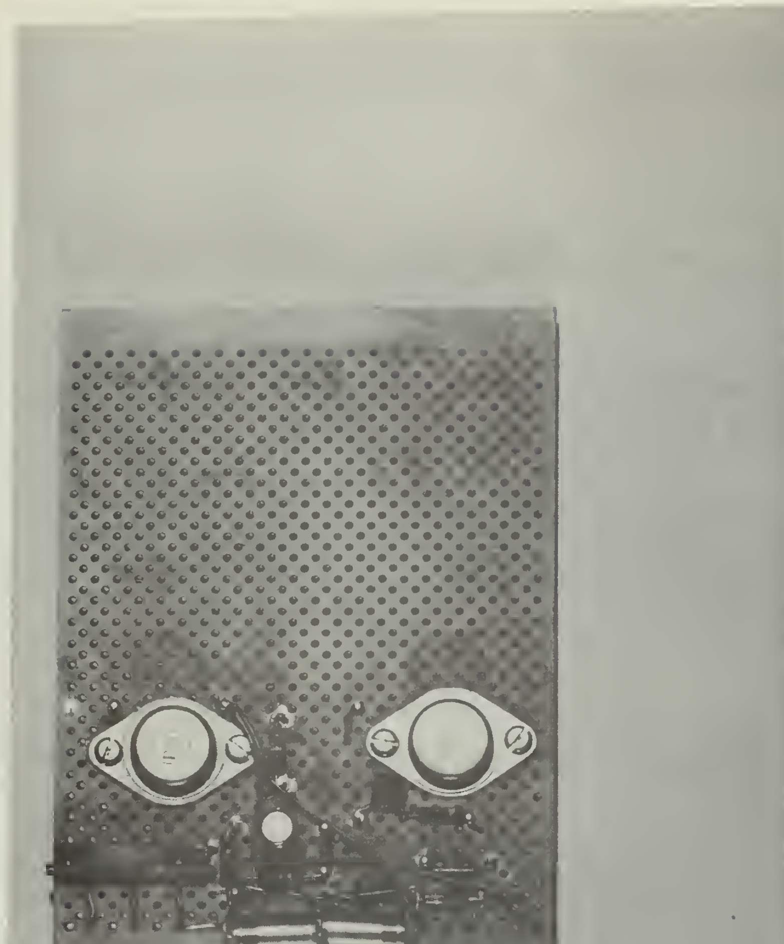

FIGURE 14. Indicator Drive Circuit Mounted on Plug-in Board

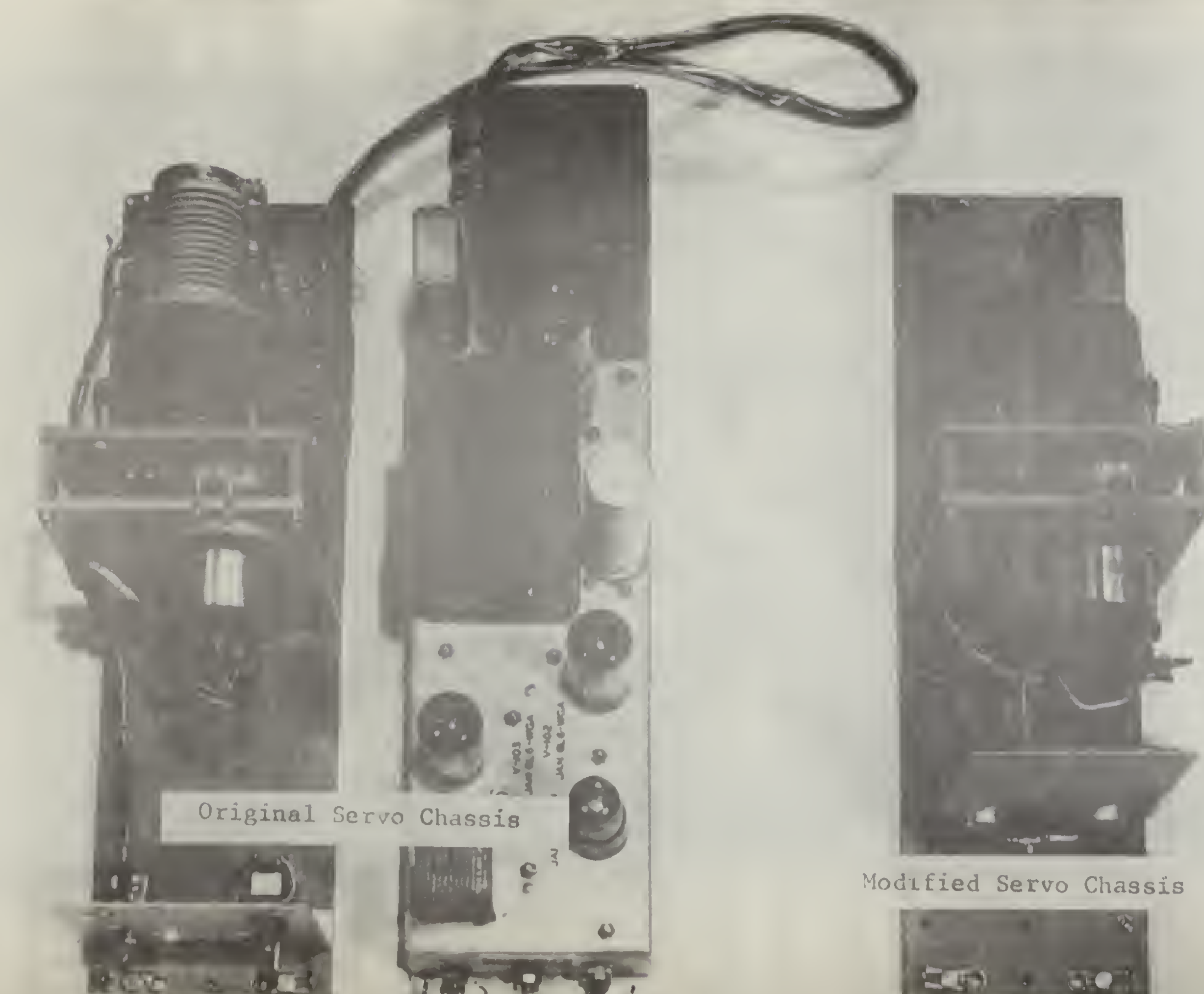

FIGURE 15. Comparison of Modified Indicator Drive Chassis with Original Servo Chassis and Servo Amplifier

follows the movement of the potentiometer. The seven modified indicator drive chassis for the previous instruments were mounted below the cockpit on the sliding racks as shown in Figure 16.

The third method for driving the instruments uses the plugboards and is employed by the accelerometer, tachometer and gyro horizon (bank only). This system was actually easier to implement and was more accurate since much of the backlash and gear inertia was eliminated. This method did not employ a servo chassis, but instead, the motor-generator inside the instrument was replaced by the d. c. motor. The follow-up potentiometer was also located within the instrument, and the plugboards and mating receptacles were mounted behind the instrument panel, close to the instruments as shown in Figure 17.

The last instrument to be modified, the pitch portion of the gyro horizon, was the one that caused the most difficulty. The original circuit did not utilize a servo chassis but used instead a complex system to drive a motor-generator in the instrument. However, this motor-generator could not be replaced by a d. c. motor as was done in the case of some of the other instruments since the motor-generator was smaller than the d. c. motor and was mounted inside the rotating hollow sphere. Since it was physically impossible to replace the motor-generator, a different system had to be designed.

After much experimentation, the circuit shown in Figure 18 was developed and mounted on a plugboard, which in turn was mounted behind the right instrument panel. The d. c. signal coming from the computer goes through a voltage divider and then to an a. c. chopper which is energized by a 15 volt a. c. reference. This reference voltage is also phase shifted by a capacitor and applied to the follow-up potentiometer. The a. c. chopper changes the d. c. signal into an a. c. signal which is

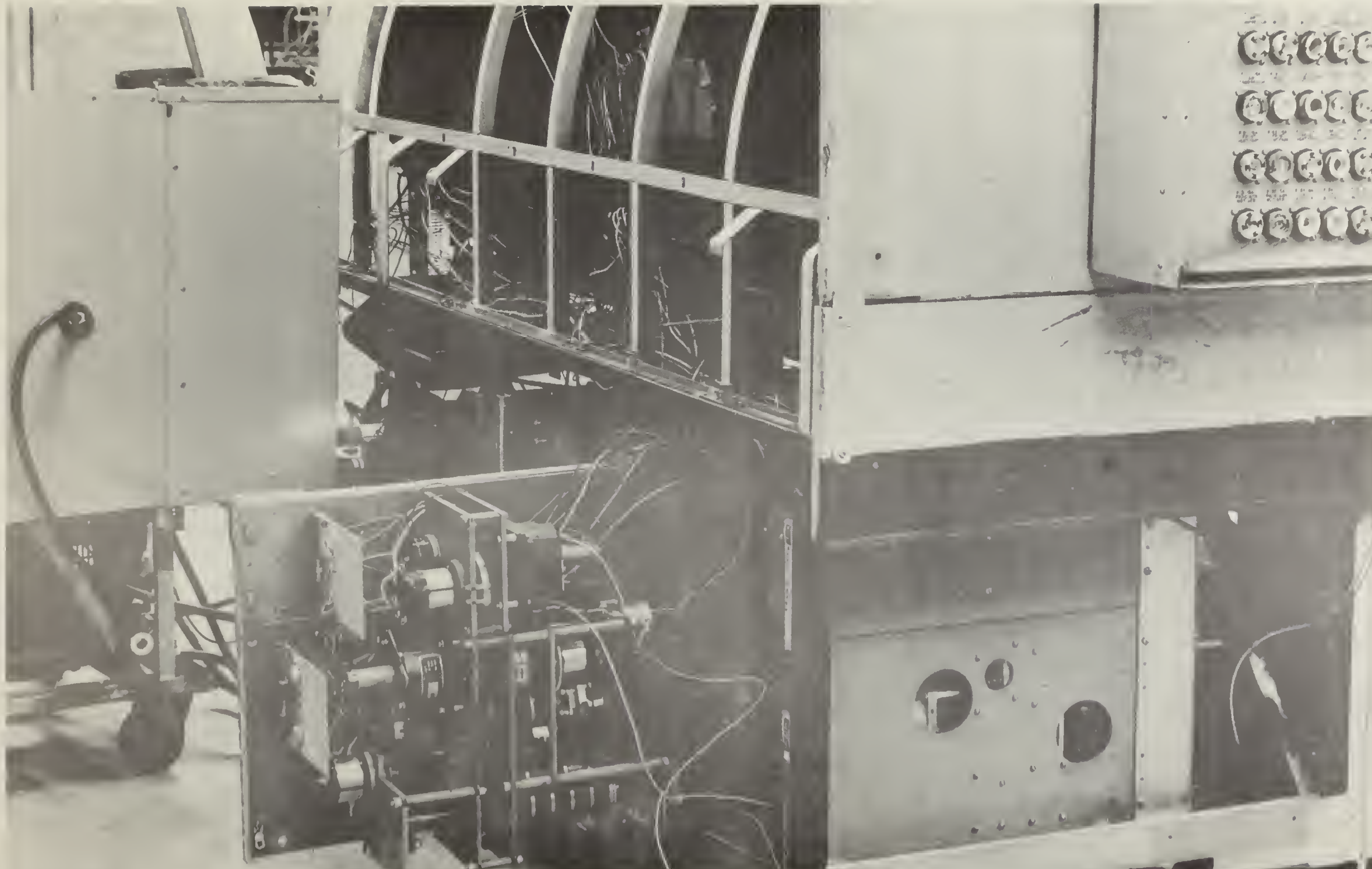

FIGURE 16. Modified Indicator Drive Chassis Mounted on Sliding Racks

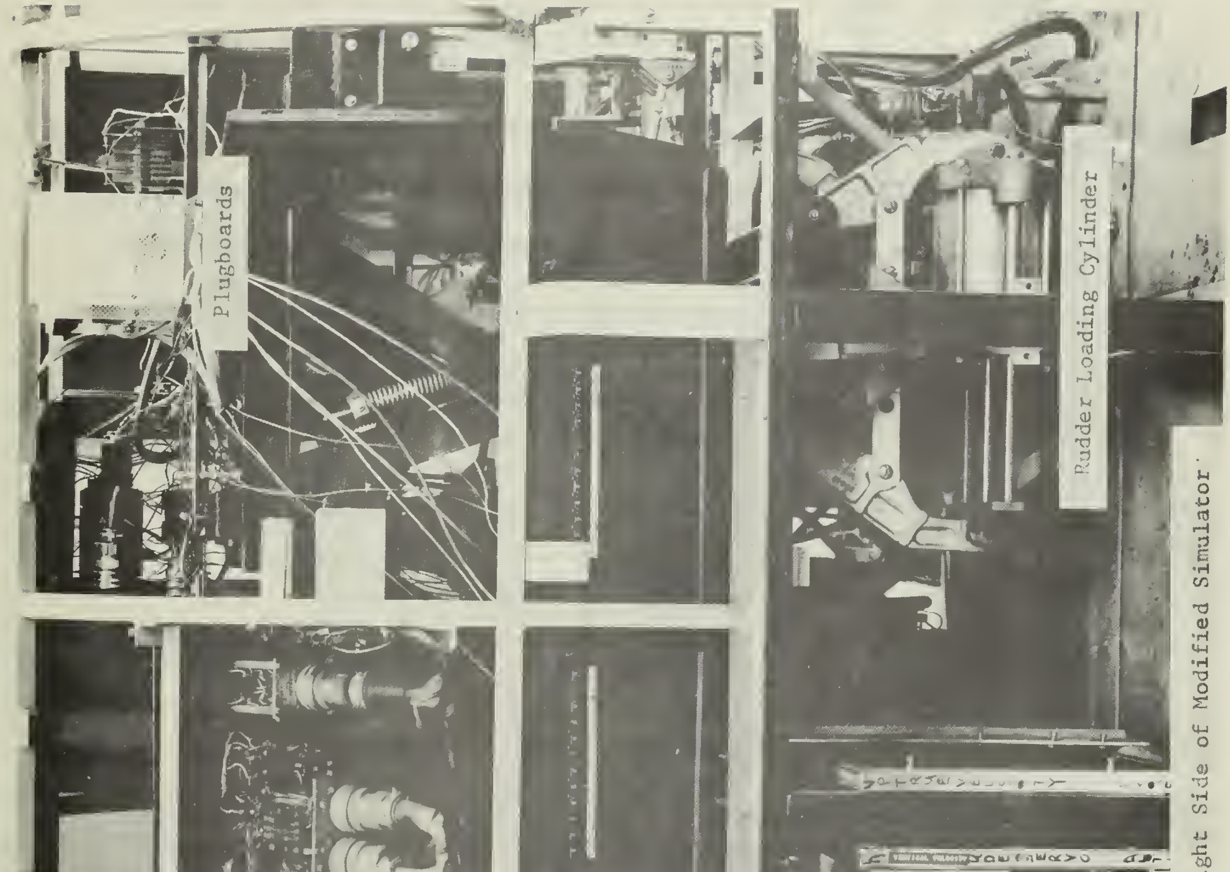

FIGURE 17. Right Side of Modified Simulator

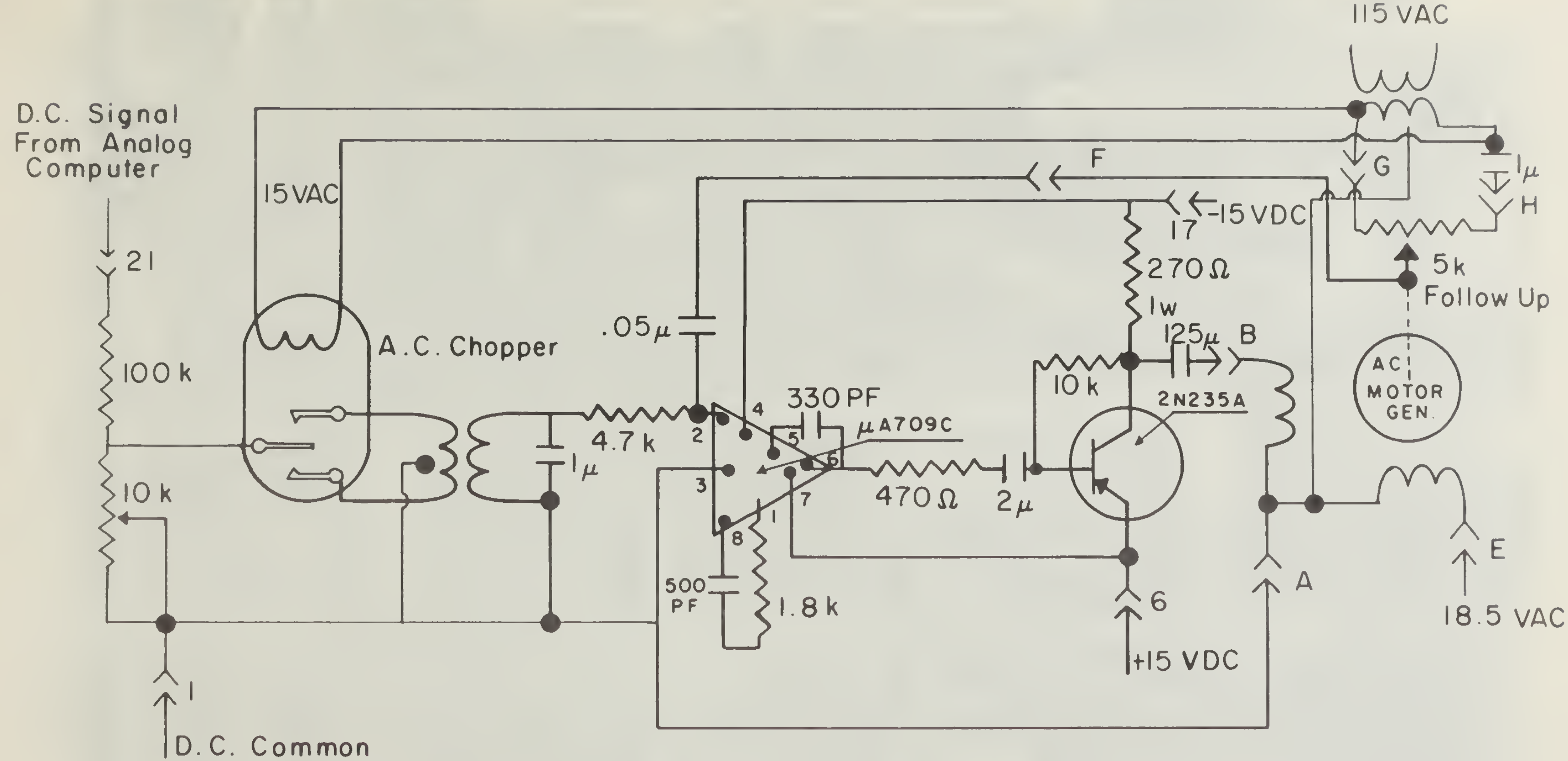

FIGURE 18. MODIFIED GYRO HORIZON (PITCH ONLY) DRIVE CIRCUIT.

essentially a square wave whose magnitude is proportional to the magnitude of the d. c. signal and whose phase depends on the polarity of the d. c. signal. This signal is smoothed somewhat and phase shifted by the transformer and summed with the follow-up signal to form an error voltage. This error voltage is amplified and controls the type 2N235A P-N-P power transistor which in turn excites one phase of the a. c. motor-generator winding. The motor-generator then turns in one direction or the other, depending on the phase relation, to drive the sphere in pitch.

CHAPTER VII

SYSTEM TEST AND CALIBRATION

After the system was installed in the laboratory, the various systems were energized and checked for proper operation. This initial check included every system except the instrument drives which had the plugboards removed for protection of the circuits. The nonfunctional instruments were set for the simulated operating altitude of 23,000 feet, and the limit and neutral switches for the trim motors were set. The pneumatic control loading system was adjusted, and the potentiometers on the elevator, aileron and rudder loading cylinders were aligned so that the neutral position was properly indicated. The throttle potentiometer was adjusted for proper operation, and the few minor discrepancies that were discovered in the various systems were corrected.

The synchro transmitters on the servo chassis were manually rotated, and the appropriate instruments were checked for proper position following. Voltage measurements were made throughout the simulator to ensure proper operation of the various power supplies and special emphasis was placed on checking the plugboard receptacles for the proper voltages with the plugboards still removed. The plugboards themselves were checked individually in a test system prior to installation in the simulator.

Each instrument drive system was aligned separately by inserting the plugboard in the proper receptacle and connecting the input terminal for that system to the d. c. common to represent the initial condition with zero input. The initial conditions were set to the desired value by rotation of the follow-up potentiometer although it could also be set by the rotation of the stator of the synchro transmitter for the instruments utilizing the synchro system. It was more difficult to set the initial conditions for the tachometer and accelerometer since the follow-up potentiometers were in the instrument case, but the other instruments were relatively easy.

The calibration of the instruments required the installation of an intercom system between the computer console and the simulator. The cable from the computer to the simulator was connected, the various d. c. voltages were applied from the computer to the simulator and the deviation from the initial condition was noted as well as the direction of the deviation. The magnitude of the deviation was set by the adjustment of the 10K potentiometers on the plugboards, and the deviations as well as the initial conditions used for the initial simulation are shown in Table I.

TABLE I

INITIAL CONDITIONS AND CALIBRATION OF FLIGHT INSTRUMENTS

Instrument	Initial Condition	Volts D. C.	Calibration
Airspeed	250 knots	-100	350 knots
Vertical Speed	0 ft/min	+100	4000 ft/min climb
Heading	000 deg.	+50	050 deg.
Angle of attack	+20 deg.	-100	+10 deg.
Gyro Horizon (Pitch)	0 deg.	-100	40 deg. up
Gyro Horizon (Bank)	0 deg.	+100	40 deg. right wing down
Rate of Turn	Centered	-20	3 needle widths to right
Ball	Centered	+100	1 ball width to right
Accelerometer	3.2g's	-100	+7.4 g's
Tachometer	55%	-100	100%
Altimeter	23,000 ft.	+50	21,500 ft.

CHAPTER VIII

HYBRID COMPUTER

The hybrid computer facility of the Naval Postgraduate School consists of a high speed digital computer model 9300 manufactured by Scientific Data Systems of Santa Monica, California, and an electronic analog computer model CI 5000 manufactured by COMCOR, Ind., of Anaheim, California, together with extensive software. Various displays are available including an X-Y recorder, a 9 channel recorder and two general purpose high performance input/output consoles which have rectangular 23 inch cathode ray tubes and light pens as well as keyboards.

The 9300 computer is a high speed, general purpose digital computer which has a core memory of 32K and a 24 bit word with extensive input/output capabilities. The various input/output devices include: teletype, paper tape, magnetic tape, light pen and analog interface. The system is operated directly by the user and utilizes Fortran IV language.

The CI 5000 is a large scale, general purpose electronic analog/hybrid computing system as shown in Figure 19. It has a total of 44 summers, 20 of which can be used as integrators, 8 inverters, 4 diode function generators, 1 electronic resolver, 10 quarter-square multipliers, 8 D/A converters and 32 A/D trunks. The present complement of equipment is approximately one-fourth of the total capacity of the system which can be rapidly expanded by additional plug-in circuits.

The analog system has a total of 32 potentiometers that are handset, but one of its time saving features is the complement of 48 servo potentiometers. These servo potentiometers are set either by buttons at the console or by a program on the digital computer. The system also has the capability of making timed runs which can be varied and introduces great flexibility to the system.

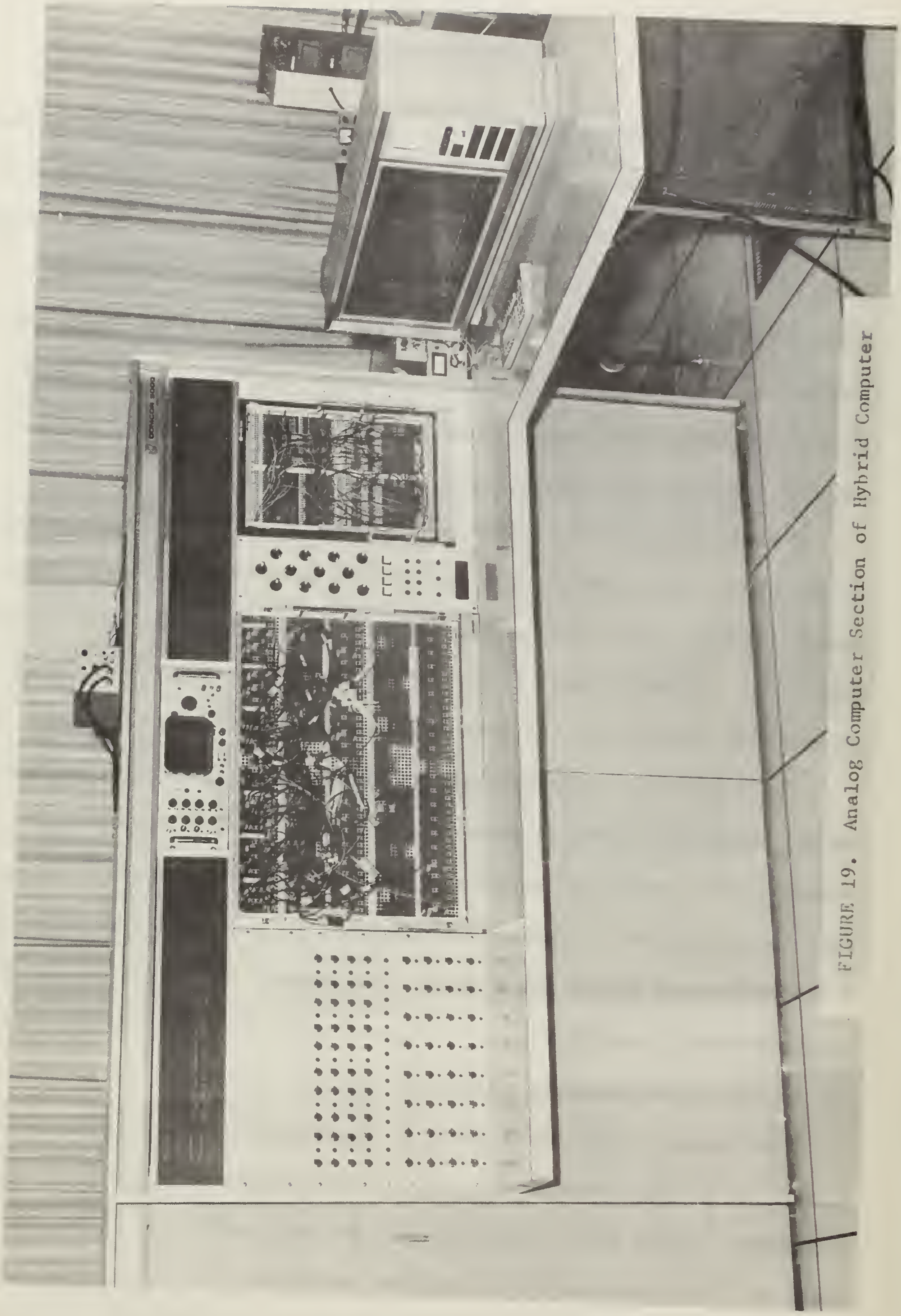

FIGURE 19. Analog Computer Section of Hybrid Computer

The analog program is set up by the use of two removable patch boards at the operator's console. The larger board is the analog patch which is used to connect the various potentiometers, summers, integrators, etc., while the smaller patch is the logic patch which is used for the various reset, hold, compute, etc., functions. The input and output connections to the simulator are made directly at the large patch board; and since the board is removable, the program can be pre-patched prior to the required demonstration, and, in addition, various thesis programs can be wired on other patch boards, allowing the simulator to be used for more than one project at a time.

The hybrid computer can be programed so that each run represents a different aircraft or so that one or more of the parameters of the same aircraft are changed on each run in a specified sequence. The system is extremely flexible; and in a large simulation problem, the fast dynamic loops can be solved by the analog portion and the slower loops by the digital portion. However, the present capacity of the analog computer severely limits the extent of the simulation problem that can be presently programed.

CHAPTER IX

CONCLUSIONS AND RECOMMENDATIONS

The variable stability simulator gives reasonably accurate representation of the response of an actual aircraft, and the characteristics of the aircraft can be readily changed on the computer without re-wiring the program. The response of the aircraft instruments could be greatly improved by the use of a servomechanism that will accept a d. c. signal to turn either a shaft or a synchro transmitter. This device could be something similar to the 900 series servo follower manufactured by Industrial Controls Company of Farmingdale, Long Island, New York.

A large scale computer program should be implemented to solve the equations of motion of any aircraft, and extensive use should be made of the flexibility of the hybrid system. Various aircraft parameters should be programed on either paper tape or punched cards for a permanent record which could be used for the class demonstrations.

Since there is a great source of aviator students at the Naval Postgraduate School, it is recommended that investigations be made in the field of flying qualities of aircraft, pilot response techniques, new flight instrumentation and pursuit-evasion techniques, all of which can be handled by the simulator and hybrid computer. The analog portion of the hybrid computer should be greatly expanded to handle the large scale problems.

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13. ABSTRACT

A C-11B Instrument Flight Trainer was converted into a variable stability flight simulator. The original frame, cockpit, controls, pneumatic system and instruments were utilized as well as certain other necessary components. The original aerodynamic and engine computers were removed, a new instrument drive system was designed and a hybrid computer was programed to solve the equations of motion. The cockpit controls supplied the inputs to the computer which in turn supplied the outputs to the various instruments through their respective drive systems. The computer program may be quickly changed to simulate the aerodynamic characteristics of almost any single engine jet aircraft, or the parameters of a specific aircraft may be varied to investigate their effects on flying qualities.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Cockpit Simulator						
Flight Simulator						
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